

Quarkonium production in deep-inelastic scattering*

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We discuss the inclusive production of J/ψ mesons in deep-inelastic scattering (DIS) via the electromagnetic, weak neutral, and charged currents within the factorization formalism of nonrelativistic quantum chromodynamics. Theoretical predictions are confronted with experimental data of ep and νN DIS taken by the H1 Collaboration at DESY HERA and the CHORUS Collaboration at CERN, respectively.

1. Introduction

Since its discovery in 1974, the J/ψ meson has provided a useful laboratory for quantitative tests of quantum chromodynamics (QCD) and, in particular, of the interplay of perturbative and nonperturbative phenomena. The factorization formalism of nonrelativistic QCD (NRQCD) [1] provides a rigorous theoretical framework for the description of heavy-quarkonium production and decay. This formalism implies a separation of short-distance coefficients, which can be calculated perturbatively as expansions in the strong-coupling constant α_s , from long-distance matrix elements (MEs), which must be extracted from experiment. The relative importance of the latter can be estimated by means of velocity scaling rules, i.e. the MEs are predicted to scale with a definite power of the heavy-quark (Q) velocity v in the limit $v \ll 1$. In this way, the theoretical predictions are organized as double expansions in α_s and v . A crucial feature of this formalism is that it takes into account the complete structure of the $Q\bar{Q}$ Fock space, which is spanned by the states $n = {}^{2S+1}L_J^{(c)}$ with definite spin S , orbital angular momentum L , total angular momentum J , and colour multiplicity $c = 1, 8$. The hierarchy of the MEs predicted by the velocity scaling rules is explained for the J/ψ , χ_{cJ} , and ψ' mesons in Table 1. In particular, this formalism predicts

the existence of colour-octet (CO) processes in nature. This means that $Q\bar{Q}$ pairs are produced at short distances in CO states and subsequently evolve into physical, colour-singlet (CS) quarkonia by the nonperturbative emission of soft gluons. In the limit $v \rightarrow 0$, the traditional CS model (CSM) [2] is recovered. The greatest triumph of this formalism was that it was able to correctly describe [3] the cross section of inclusive charmonium hadroproduction measured in $p\bar{p}$ collisions at the Fermilab Tevatron [4], which had turned out to be more than one order of magnitude in excess of the CSM prediction.

Table 1

Values of k in $\langle \mathcal{O}^H[n] \rangle \propto v^k$ for $H = J/\psi, \chi_{cJ}, \psi'$.

k	$J/\psi, \psi'$	χ_{cJ}
3	${}^3S_1^{(1)}$	—
5	—	${}^3P_J^{(1)}, {}^3S_1^{(8)}$
7	${}^1S_0^{(8)}, {}^3S_1^{(8)}, {}^3P_J^{(8)}$	—

In order to convincingly establish the phenomenological significance of the CO processes, it is indispensable to identify them in other kinds of high-energy experiments as well. Studies of charmonium production in ep photoproduction, ep and νN deep-inelastic scattering (DIS), e^+e^- annihilation, $\gamma\gamma$ collisions, and b -hadron decays may be found in the literature; see Ref. [5] and references cited therein. Here, N denotes a nucleon. Furthermore, the polarization of charmonium, which also provides a sensitive probe of CO processes, was investigated [6,7]. Until very recently, none of these studies was able to prove

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or disprove the NRQCD factorization hypothesis. However, preliminary data of $\gamma + \gamma \rightarrow J/\psi + X$ taken by the DELPHI Collaboration [8] at LEP2 provide first independent evidence for it [9].

In this presentation, we review recent studies of J/ψ inclusive production in DIS via the electromagnetic [10], weak neutral (NC) [11], and charged currents (CC) [12] to lowest order (LO) in the NRQCD factorization formalism.

2. ep DIS via the electromagnetic current

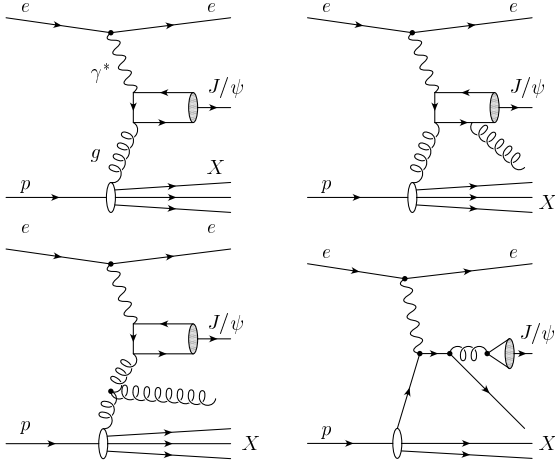


Figure 1. Feynman diagrams for $e + p \rightarrow e + J/\psi + X$ in DIS.

The Feynman diagrams for $e + p \rightarrow e + J/\psi + X$ in DIS are depicted in Fig. 1. This process allows for a particularly clean test of the NRQCD factorization hypothesis, since the large photon virtuality Q^2 ensures that perturbative QCD is applicable and that the resolved-photon contribution, which suffers from our imperfect knowledge of the parton density functions (PDFs) of the photon, is greatly suppressed. Diffractive processes, which cannot yet be reliably described within purely perturbative QCD, can be excluded by imposing an upper cutoff on the elasticity variable z , which also eliminates the γ^*g fusion process (first diagram in Fig. 1). The diagrams in the lower panel correspond to CO processes, while the right one in the upper panel already contributes in the CSM.

In Figs. 2 and 3, our CSM and NRQCD predictions [10] are confronted with data from the H1

Collaboration at HERA [13]. Here, $p_{t,\psi}$ and Y are the J/ψ transverse momentum and rapidity, respectively, W is the γ^*p invariant mass, and quantities referring to the γ^*p centre-of-mass frame are denoted by an asterisk. We take the charm-quark mass to be $m_c = 1.5$ GeV, employ the LO proton PDFs from Ref. [14], with $\Lambda^{(3)} = 204$ MeV, adopt the corresponding MEs from Ref. [7], and choose the renormalization and factorization scales to be $\mu = M = \sqrt{Q^2 + 4m_c^2}$. The theoretical uncertainties are conservatively estimated by taking into account the experimental errors on m_c and the MEs and the well-known ambiguity between $\langle \mathcal{O}^{J/\psi} [^1S_0^{(8)}] \rangle$ and $\langle \mathcal{O}^{J/\psi} [^3P_0^{(8)}] \rangle$ [15], using alternative proton PDFs, and varying the scales. As for the normalization, the H1 data clearly favours the NRQCD prediction (see Fig. 2). On the other hand, the shapes of the various distributions exhibit a diverse pattern (see Fig. 3). While the H1 measurement nicely agrees with NRQCD in the normalized $p_{t,\psi}^2$ and $p_{t,\psi}^{*2}$ distributions, it favours the normalized z distribution of the CSM, which distinctly undershoots the NRQCD prediction in the upper z range. The latter feature is familiar from inclusive J/ψ photoproduction at HERA [15].

3. νN DIS via the weak neutral current

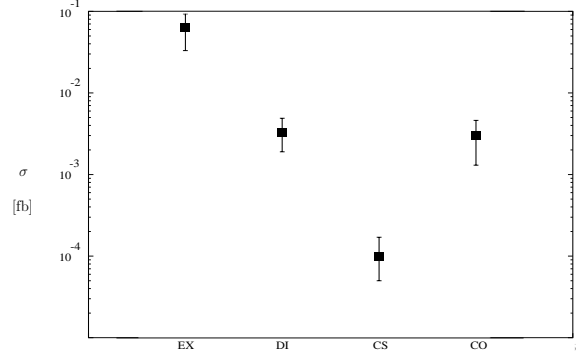


Figure 4. The total cross section of $\nu + \text{Pb} \rightarrow \nu + J/\psi + X$ measured by CHORUS [16] (EX) is compared with the predicted [11] diffractive (DI), CS, and CO contributions.

The total cross section of $\nu + N \rightarrow \nu + J/\psi + X$ in NC DIS was recently measured by the CHO-

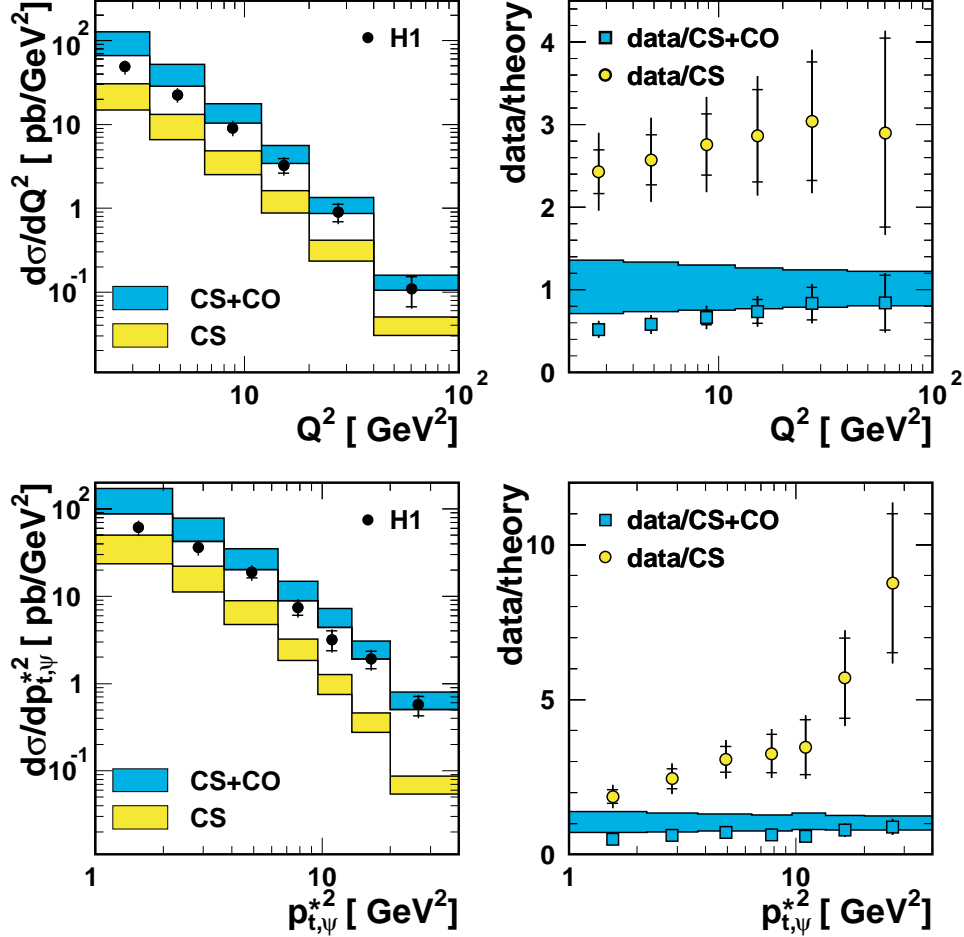


Figure 2. Comparison of the CSM and NRQCD predictions [10] for the Q^2 and $p_{t,\psi}^2$ distributions of $e + p \rightarrow e + J/\psi + X$ with H1 data [13].

RUS Collaboration [16], who exposed a lead target in the CERN wide-band neutrino beam. No acceptance cuts were imposed to exclude the Z^*g -fusion and diffractive processes, so that their contributions have to be included in the theoretical prediction. Furthermore, no selection of directly produced J/ψ mesons was implemented, and those from χ_{cJ} and ψ' decays need to be considered, too. However, the fraction of J/ψ mesons from B decays should be negligible [11]. In Fig. 4, the CHORUS result, $(6.3 \pm 3.0) \times 10^{-2}$ fb, is compared with our predictions [11] for the diffractive, CS and CO contributions. The diffractive contribution is estimated by means of the vector-

meson dominance model as in Ref. [17]. The combined prediction undershoots the CHORUS central value by almost one order of magnitude, but the experimental error is still rather sizeable.

4. ep and νN DIS via the charged current

The reaction $\nu + N \rightarrow l^\pm + J/\psi + X$ proceeds through the Feynman diagrams depicted in Fig. 5. If the hadronic remnant X is charmless, then we are dealing with a CO process. Otherwise, both CS and CO channels contribute. Since the W boson cannot fluctuate into charmonia, there are no diffractive processes. For the total cross section

of prompt J/ψ production under CHORUS experimental conditions, we find $4.9^{+3.4}_{-2.3} \times 10^{-5}$ fb in the charmless- X mode and $1.8^{+1.5}_{-0.9} \times 10^{-5}$ fb in the charmed- X mode.

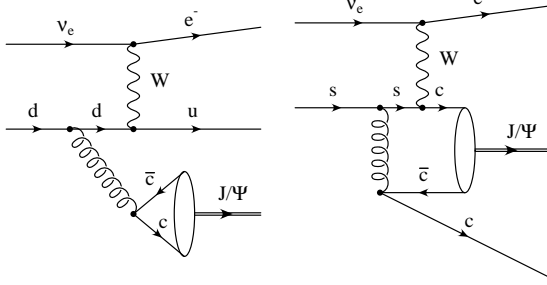


Figure 5. Feynman diagrams for $\nu + N \rightarrow l^\pm + J/\psi + X$ in DIS.

5. Conclusions

Inclusive J/ψ production in DIS lends itself as a sensitive probe of the CO mechanism. As for $e + p \rightarrow e + J/\psi + X$, the H1 data [13] generally confirms NRQCD and disfavours the CSM [10]. However, NRQCD predicts at LO a distinct rise in cross section as $z \rightarrow 1$, which is not reflected by the H1 data. This anomaly is familiar from photoproduction, and it is likely to be resolved by the inclusion of higher-order corrections [15], possibly in combination with intrinsic- k_T effects and/or nonperturbative shape functions. As for $\nu + N \rightarrow \nu + J/\psi + X$, the CHORUS central value for the total cross section [16] exceeds the LO prediction [11] by almost one order of magnitude. However, the experimental error is still rather sizeable. As for $\nu + N \rightarrow l^\pm + J/\psi + X$, CO processes are dominant, diffractive ones are absent, and the experimental signature is spectacular, so that a measurement would be worthwhile [12]. Inclusive J/ψ production in CC DIS represents a challenge for HERA and THERA.

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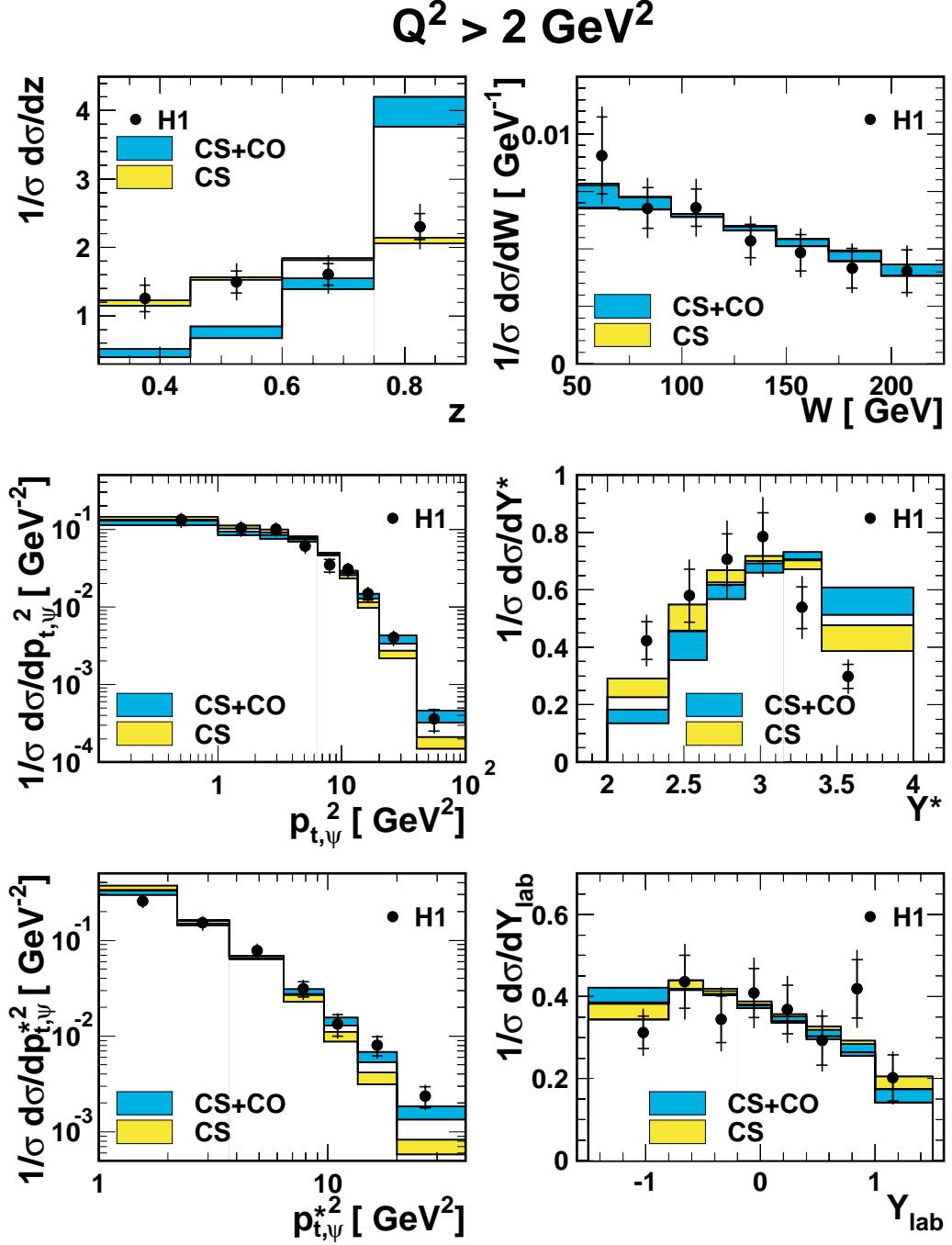


Figure 3. Comparison of the CSM and NRQCD predictions [10] for the normalized z , W , $p_{t,\psi}^2$, Y^* , $p_{t,\psi}^{*2}$, and Y_{lab} distributions of $e + p \rightarrow e + J/\psi + X$ with H1 data [13].